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Hybrid 3D-Printed/Electrospun Honeycomb PCL Scaffolds Improve Mechanical Stability and Promote Osteoblast Colonization

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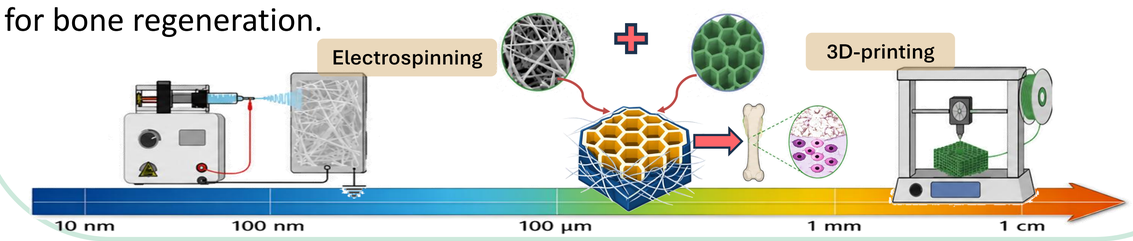
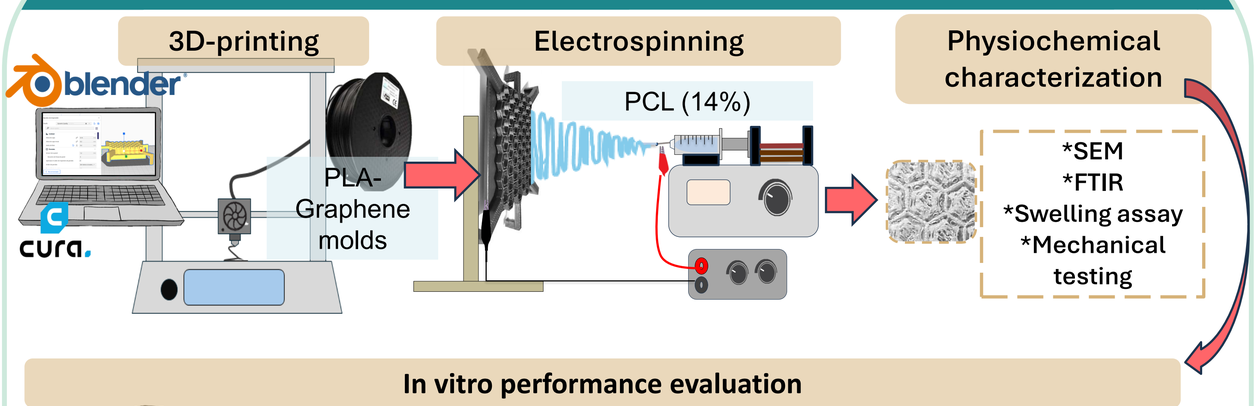
INTRODUCTION & AIM

The development of biomaterials and biomimetic scaffolds capable of guiding tissue regeneration remains a major challenge in bone tissue engineering. Beyond providing structural support, scaffolds must recreate key physicochemical and architectural features of the extracellular microenvironment to regulate cellular responses and promote tissue formation. Electrospinning enables the production of nanofibrous matrices that resemble the extracellular matrix but lacks control over macroscopic geometry and mechanical robustness. In contrast, 3D printing allows precise architectural design but does not replicate the nanoscale features required for optimal cell–material interactions. Therefore, this study proposes a hierarchical approach that combines both techniques to fabricate honeycomb-shaped scaffolds designed to modulate cell–material interactions while providing structural support for bone regeneration.

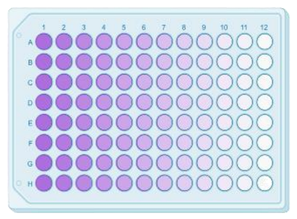


METHODS

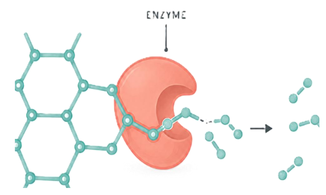


In vitro performance evaluation

Confocal and fluorescence microscopy (Cell tracker staining)



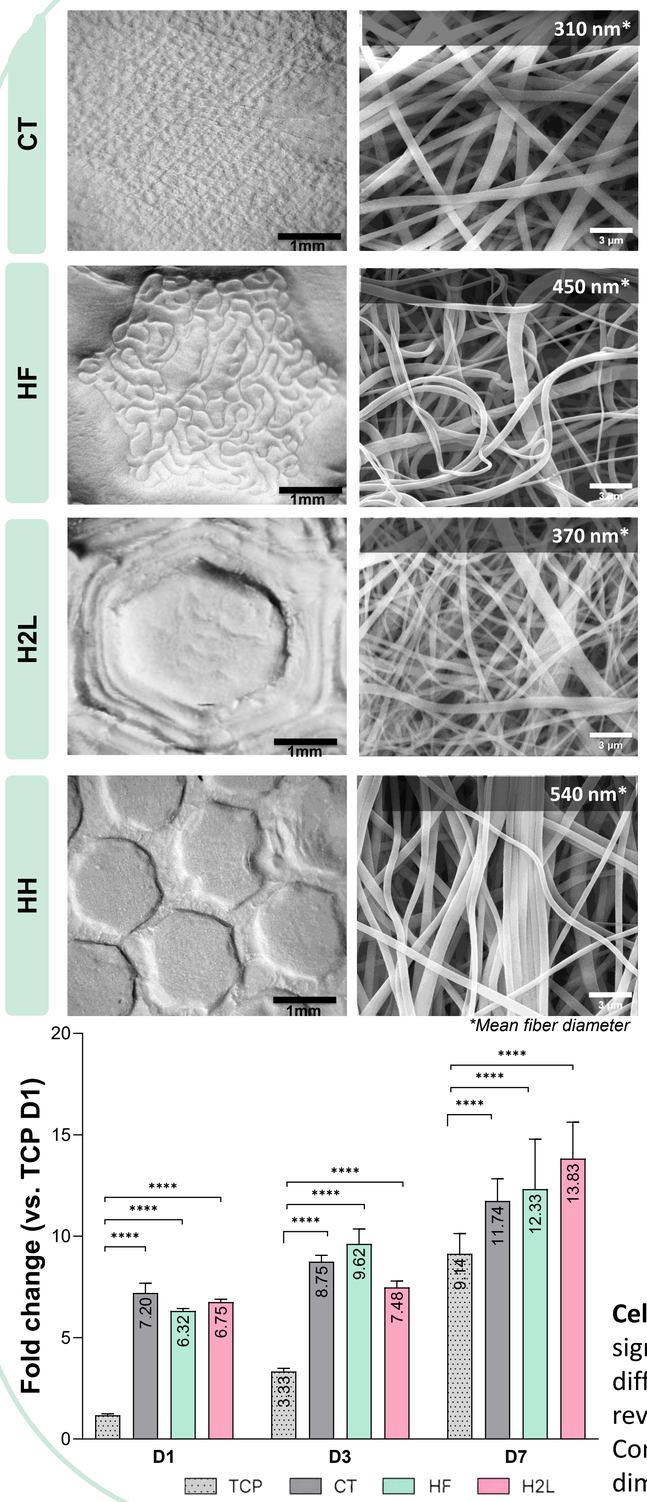
MTT cell viability testing

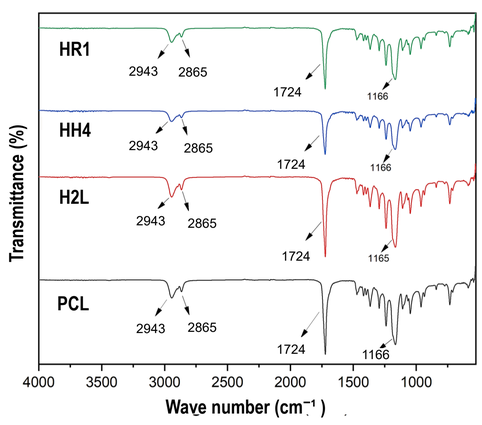


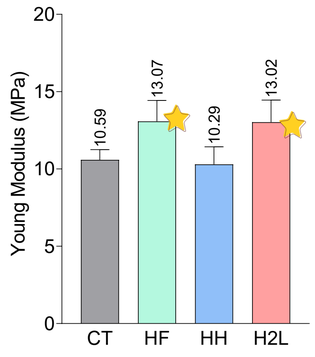
Lipase degradation at physiological concentration

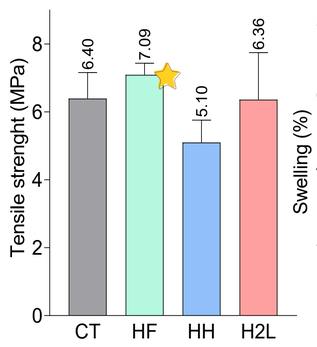
Human Fetal Osteoblasts

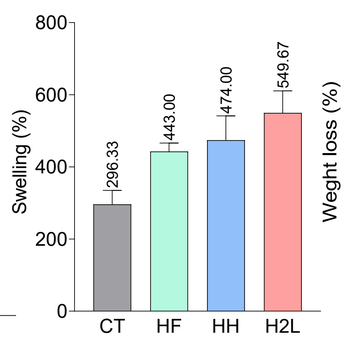
RESULTS & DISCUSSION

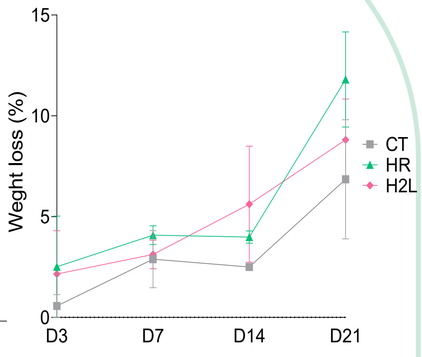




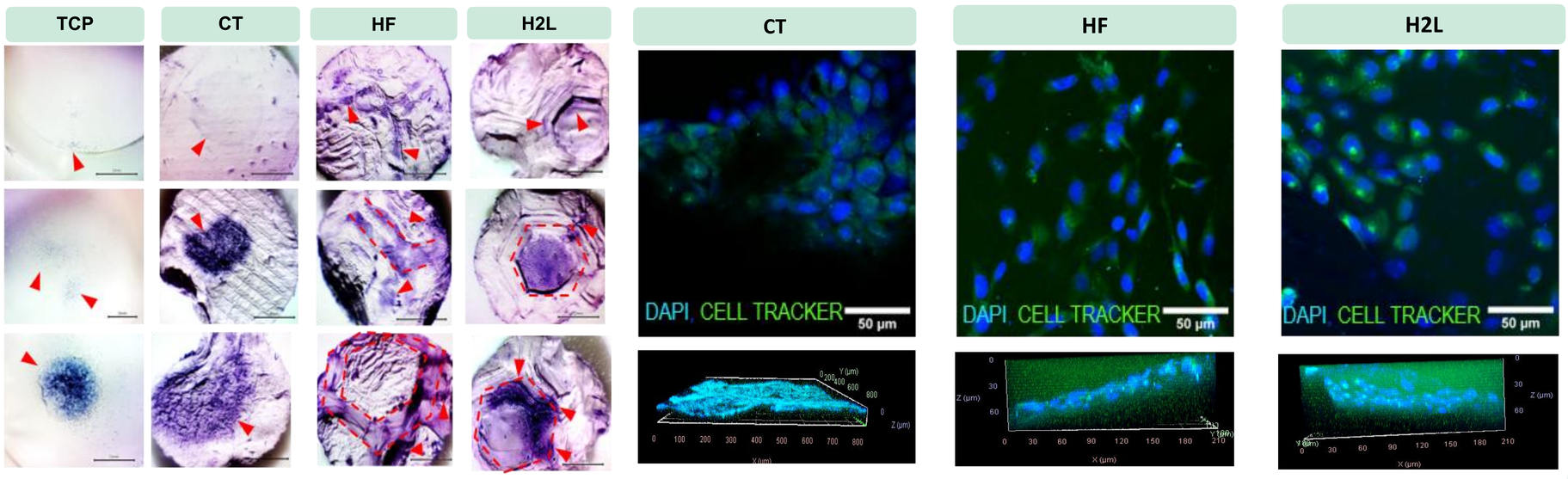








Morphological and Physicochemical Characterization. SEM micrographs confirmed the successful fabrication of all scaffold architectures, revealing distinct surface morphologies and fiber organizations. Fiber diameters ranged from approximately 310–540 nm depending on design. FTIR spectra exhibited the characteristic bands of PCL, including C–H stretching (2943 and 2865 cm^{-1}), ester carbonyl (1724 cm^{-1}), and C–O–C vibrations (1176 cm^{-1}). No additional bands were detected, indicating that the fabrication process did not alter the chemical composition of the polymer. Scaffold architecture significantly influenced mechanical behavior. HF exhibited the highest Young's modulus and tensile strength, indicating increased stiffness and resistance to failure. These findings suggest that the hexagonal architecture modifies stress distribution within the scaffold. Based on the combined mechanical performance and structural characteristics, HF and H2L were selected for subsequent biological evaluation. Swelling capacity varied according to scaffold design, with H2L showing the highest water uptake. Under physiological lipase conditions, hexagonal scaffolds exhibited greater mass loss than the control over 21 days, suggesting that architecture-dependent differences in exposed surface area may influence degradation behavior.



Cell Viability and Colonization. Human fetal osteoblasts remained metabolically active on all electrospun scaffolds throughout culture. MTT results showed significantly higher activity than those on tissue culture plastic, confirming scaffold biocompatibility. Qualitative observations revealed architecture-dependent differences in cell distribution and colonization patterns, indicating that scaffold geometry modulates cell–material interactions. Fluorescence microscopy revealed well-defined nuclei (DAPI) and an extended cellular morphology (CellTracker), consistent with adequate adhesion and spreading on all scaffold types. Confocal Z-stack reconstructions demonstrated cell presence at multiple depths throughout the scaffolds, indicating that the porous architecture supports three-dimensional cellular colonization and infiltration.

CONCLUSIONS & FUTURE WORK

This study demonstrates that scaffold geometry is not merely a structural feature but a key regulator of biomaterial performance. By combining 3D printing and electrospinning, it was possible to generate hierarchical honeycomb architectures that modulated mechanical behavior, degradation kinetics, and cell–material interactions while maintaining the intrinsic properties of PCL. The ability of these scaffolds to support osteoblast viability, colonization, and infiltration highlights their potential as customizable platforms for bone tissue engineering and regenerative medicine applications. Future work will focus on investigating the osteogenic differentiation of mesenchymal stem cells (MSCs) cultured within these scaffolds and determining how architecture-driven cues influence cell fate and tissue formation. These studies will contribute to the development of next-generation biomaterial platforms capable of actively directing bone regeneration.

REFERENCES & ACKNOWLEDGMENT

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References and contact information